Arch Environ Contam Toxicol (2008) 54:504–515
DOI 10.1007/s00244-007-9058-5

Biomagnification of Trace Elements in the Aquatic Food Web in the Mekong Delta, South Vietnam Using Stable Carbon and Nitrogen Isotope Analysis

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Received: 28 September 2007 / Accepted: 1 October 2007 / Published online: 17 November 2007

Abstract In the present study, we report the concentrations of 21 trace elements (V, Cr, Mn, Co, Cu, Zn, As, Se, Rb, Sr, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Hg, Tl, Pb, and Bi), as well as the results of the analysis of stable carbon and nitrogen isotopes, of the various biota that make up the food web in the main stream of the Mekong Delta near Can Tho, South Vietnam. A significant trophic level-dependent increase was found in concentrations of Se, Rb, and Hg with increasing δ^{15}N, indicating that an overall biomagnification of these elements occurred. However, the increase of Hg concentration per trophic level was lower than in previous studies. In contrast, the concentration of Mn showed an opposite trend in the food web of the Mekong Delta. In addition to these overall trends, the present study revealed that the biomagnification profiles of trace metals differ between crustaceans and fishes; concentrations of Mn, Cu, Zn, As, Sr, Mo, Ag, Cd, Sb, Cs, Ba, Tl, and Pb were significantly higher in crustaceans, whereas fishes showed higher concentrations of Cr, Rb, and Hg (trophic level determined by δ^{15}N). The differences in the biomagnification profile between the major taxa might be attributed to differences in metal accumulation and in detoxification abilities such as possessing a metal-binding protein, e.g., metallothionein (MT).

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Introduction

Southeast and south Asian countries have undergone rapid economic development with increases of populations during the last several decades. Environmental pollution by trace metals and organochlorines, caused by increased anthropogenic activities, has been reported in recent studies (e.g., Monirith et al. 2003; Minh et al. 2003; Agusa et al. 2003). Notably, in several delta areas, i.e., the Bengal Delta in Bangladesh, the Mekong Delta, and the Red River Delta in Vietnam, as the use of groundwater has increased, people have been faced with the risk of drinking As-contaminated groundwater (Nordstrom 2002; Iwata et al. 2004; Agusa et al. 2006; Stanger et al. 2005).

The Mekong Delta area plays a very important role in Vietnamese agriculture and, recently, it became one of the most agriculturally productive areas in Southeast Asia. The population of Can Tho, which is situated in the middle of the Mekong Delta, has been rapidly increasing to be now more than a 1 million. An increase in environmental contamination by various chemicals such as heavy metals and persistent organochlorines is anticipated in the city. In fact, a recent study conducted in the Mekong Delta revealed that

concentrations of As, Mn, and Ba in the groundwater collected from several locations exceeded World Health Organization (WHO) drinking-water guidelines (Iwata et al. 2004; Stanger et al. 2005). These studies led to anxieties that large aquatic fishes and shrimps would be contaminated with these trace metals. Therefore, understanding the trophic transfer of environmental contaminants from water to large animals of high trophic levels in the Mekong Delta ecosystem is critical to evaluating the influence of these contaminants on the ecosystems and human life.

Traditionally, the estimation of the biomagnification of contaminants through a food web has been based on comparisons of tissue contaminant concentrations obtained from laboratory experiments on members of particular trophic levels with published aquatic food-web models, and data on feeding behavior or stomach contents (Suedel et al. 1994). Recently, there have been rapid advances in modeling the cycling of compounds using the stable isotope ratios of bioelements such as the carbon and nitrogen. In general, $^{15}N/^{14}N$ ($\delta^{15}N$) is on average 3–5‰ higher in a predator relative to its prey (DeNiro and Epstein 1981; Minagawa and Wada 1984; Hobson and Welch 1992). Thus, $\delta^{15}N$ can be used to characterize the trophic positions of organisms in the food web. In contrast, $\delta^{13}C$ only slightly increases with increasing trophic level (about 1‰); it is mostly used to identify ultimate carbon sources in the food web (Peterson and Fry 1987). Consequently, $\delta^{15}N$ has been used to estimate the biomagnification of mercury and organochlorines in marine and aquatic food webs in the last decade (Cabana and Rasmussen 1994; Kidd et al. 1995a; Atwell et al. 1998; Moisey et al. 2001; Mackintosh et al. 2004). However, to the authors' knowledge, few studies using $\delta^{15}N$ to estimate the biomagnification of multiple trace elements in tropical aquatic food webs have been reported except for that by Yoshinaga et al. (1992). Therefore, the present study was conducted to evaluate the basic structure of a food web using $\delta^{13}C$ and $\delta^{15}N$ in the Mekong Delta ecosystem near Can Tho in South Vietnam and to clarify the trophic transfer of 21 trace elements in the biota of the ecosystem.

Materials and Methods

Sample Collection

Sampling was conducted in the Mekong Delta near Can Tho, South Vietnam (Fig. 1). Because baseline $\delta^{15}N$ values may vary from ecosystem to ecosystem, owing to differences in anthropogenic nutrient inputs (Cabana and Rasmussen 1996; Cole et al. 2004), it was crucial that all study biota were collected from one ecosystem. Therefore, all sampling was conducted in or along the main stream of the Mekong River near Can Tho (45°10′N, 141°15′E) on

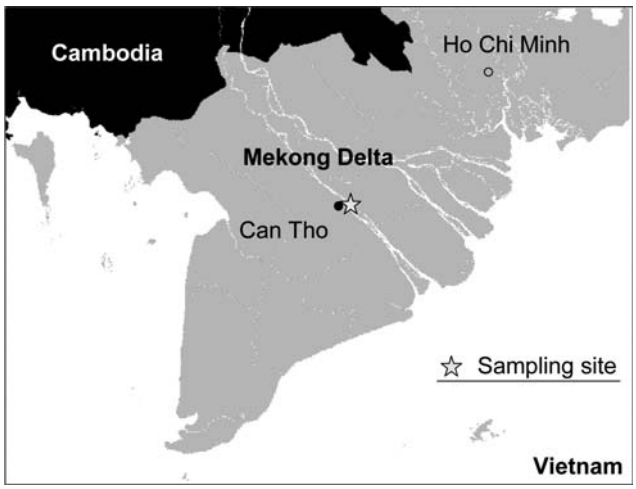

Fig. 1 Sampling locations of organisms and waters in the Mekong Delta of southern Vietnam

23 and 24 April 2004. Fish, crustacean, and gastropod samples were purchased directly from local fishermen operating in the main stream of the Mekong River. Phytoplankton and particulate organic matter (POM) were collected by towing a North Pacific plankton net (NORPAC) (0.10 mm in mesh size) horizontally using small boats. In the laboratory, the samples collected by the net were gently transferred to plastic bottles and kept in a refrigerator for two to four hours. The organisms were naturally divided into two layers: a green layer that formed near the surface of the bottle and that was composed of phytoplankton, and a brown one sunk to near the bottom of the bottle and was recognized as POM. The phytoplankton, POM, and the other parts of the water column were clearly distinguishable. Water samples were collected directly from the surface of the Mekong Delta using polyethylene bottles. These samples were kept frozen at −20°C until dissection and chemical analysis.

Stable Carbon and Nitrogen Isotope Analysis

Stable carbon and nitrogen isotope ratios were determined using the procedure described previously by Okuda et al. (2004). In general, in animals of higher trophic levels, the difference in the carbon and nitrogen isotope ratio between an empty and a full digestive tract is greater than in animals of lower trophic levels. Thus, in order to avoid contamination by the biota in the digestive tracts, the muscle tissues of fish, crustaceans, and gastropods were used for the stable isotope samples. All samples were dried for 24 hr at 60°C. They were ground to a powder and then immersed in a chloroform:methanol (2:1) solution for 24 hr to remove lipids. Stable carbon and nitrogen isotopes were measured using a gas chromatography–combustion–isotope ratio

mass spectrometer (GC-C-IRMS) (PDZ Europa Ltd, ANCA-SL). Results are presented as per thousand deviations from the standards, expressed as $\delta^{13}C$ and $\delta^{15}N$ by the following equation:

$$\delta X\,(\%) = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000,$$

where X is ^{13}C or ^{15}N and R is the corresponding ratio $^{13}C/^{12}C$ or $^{15}N/^{14}N$. Pee Dee belemnite (PDB) limestone carbonate and atmospheric nitrogen (N_2) were used as the standards for carbon and nitrogen isotope ratios, respectively.

Trace Element Analysis

The water samples were filtered (pore size: 0.45 μm) and acidified with H_2SO_4 for As and with HNO_3 for other elements. MilliQ water acidified with H_2SO_4 or HNO_3 was used as a control. Whole homogenized biological samples were dried for 12 hrs at 80°C. The average moisture contents were found to be 96.2% in phytoplankton, 74.8% in POM, 73.5 ± 3.5% in crustaceans, and 77.0 ± 2.5% in fish. Concentrations of trace elements were determined using the procedure described previously by Nam et al. (2005). About 0.2 g of the sample was digested in 5 ml of concentrated HNO_3 in a microwave system for 30 min (MILESTONE, ETHOS D microwave laboratory system). The concentrations of 18 trace elements (V, Cr, Mn, Co, Cu, Zn, Rb, Sr, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Tl, Pb, and Bi) were measured with an inductively coupled plasma mass spectrometer (ICP-MS) (Hewlett-Packard, HP-4500). Yttrium was used as the internal standard. Concentrations of Se and Hg were determined with a hydride generation atomic absorption spectrometer (Hitachi, Model HFS-3) and a cold vapor atomic absorption spectrometer (Sanso, Model HG-3000), respectively. For As analysis, the sample was digested with an acid mixture (HNO_3:H_2SO_4:$HClO_4$ = 1:1:2) in a Kjeldahl flask by heating until white fumes disappeared (Kubota et al. 2001). Arsenic content was determined by a hydride generation atomic absorption spectrometer (Shimadzu, HVG-1 hydride system). To guarantee the accuracy and precision of the methods, standard reference materials DORM2 (National Research Council Canada) were used. Recoveries of Cr, Mn, Co, Cu, Zn, As, Se, Ag, Cd, Hg, and Pb ranged from 86.0 to 116%. The precision of the method (expressed as coefficient of variation) for replicate samples was better than 10%.

Statistical Analyses

One-half of the respective limit of detection was substituted for those values below the limit of detection and was used in statistical analyses. When >50% of the observations were below the detection limit, further statistical analyses were not conducted. All data were tested for goodness of fit to a normal distribution with a Kolmogorov–Smirnov one-sample test. Because the concentrations of many elements follow a normal distribution, parametric tests were used. Single regression analysis was conducted between the stable isotopes values and trace element concentrations. Analysis of variance (ANOVA) was used to compare the concentrations of trace elements between crustaceans and fish. Furthermore, when relationships between $\delta^{15}N$ value and trace element levels were significant, analysis of covariance (ANCOVA), with the $\delta^{15}N$ value as a covariate, was used. A p value of less than 0.05 was considered to indicate statistical significance. These analyses were carried out with StatView software (version 5.0, SAS Institute).

Results

Food Web Structure

Stable isotope analysis was based on the following samples: phytoplankton, POM, one species of gastropod, five crustacean species, and 15 fish species (Table 1). A food web based on the phytoplankton was examined and the $\delta^{13}C$ and $\delta^{15}N$ values ranged from −23 to −22‰ and 9 to 18‰, respectively (Fig. 2). The data point cluster of $\delta^{13}C$ and $\delta^{15}N$ (Fig. 2) is triangular with the base spanning a wide range of $\delta^{13}C$. This profile indicated that there were several primary food sources, including the phytoplankton and/or that the biota of higher trophic levels prey on each other. Assuming that the values for the phytoplankton were those of the lowest level at 10.1‰ ($\delta^{15}N$), the difference of $\delta^{15}N$ values between phytoplankton and the fish *Polynemus paradiseus*, which belongs to the highest trophic level, was estimated to be 6.4‰. Since $\delta^{15}N$ increased on average 3–5‰ per trophic level (DeNiro and Epstein 1981; Minagawa and Wada 1984; Hobson and Welch 1992), our findings indicated that the food web of the main stream of the Mekong Delta consisted of three trophic levels.

Trace Element Concentrations in the Water and Biota

Concentrations of trace elements in water were shown in Table 2. Of the 21 elements analyzed, the concentration of Sr was highest (mean, 120 μg/l), followed by Ba (25 μg/l), Mn (3.57 μg/l), Rb (2.57 μg/l), As (1.6 μg/l), Zn (1.41 μg/l), Cu (1.40 μg/l), and V (1.1 μg/l). On the other hand, the

Table 1 Biometry of organisms from the Mekong Delta, South Vietnam

Species	ID	Body length (mm)		Body weight (g)		n^a	n^b
		Mean ± SD	(Min–Max)	Mean ± SD	(Min–Max)		
Phytoplankton		–		–		6	1
POM		–		–		6	1
Snail 1		–		0.5 ± 0.1	(0.4–0.6)	3	–
Crustaceans							
Macrobrachium rosenbergii	S1	98.8 ± 35.3	(60.4–138.9)	34.5 ± 31.2	(6.7–79.3)	5	5
Macrobrachium equidens	S2	41.5 ± 10.4	(25.5–60.7)	2.2 ± 1.6	(0.3–7.6)	37	7
Macrobrachium sp. 3	S3	79.7 ± 11.6	(60.6–89.2)	11.5 ± 4.7	(4.4–15.9)	6	2
Macrobrachium sp. 4	S4	33.0 ± 7.4	(23.9–42.0)	0.7 ± 0.5	(0.2–1.3)	14	3
Metapenaeus tenuis	S5	52.7 ± 4.4	(46.8–57.8)	1.9 ± 0.4	(1.3–2.5)	7	1
Fish							
Clupeoides sp.	F1	35.8 ± 3.6	(31.0–40.0)	0.7 ± 0.2	(0.5–0.9)	6	1
Pisodonophis boro	F2	492.9 ± 58.0	(413.3–564.9)	28.6 ± 10.1	(18.1–46.0)	6	2
Rasbora aurotaenia	F3	66.8 ± 3.5	(63.6–70.5)	2.8 ± 0.4	(2.4–3.1)	3	–
Stenogobius mekongensis	F4	41.6 ± 5.1	(37.4–47.3)	1.5 ± 0.7	(0.9–2.2)	3	–
Eleotris melanosoma	F5	71.9	(68.0–75.7)	11.0	(9.0–13.0)	2	1
Polynemus paradiseus	F6	53.6 ± 14.8	(33.1–82.8)	3.4 ± 2.8	(0.6–9.6)	12	3
Glossogobius aureus	F7	81.5 ±27.8	(42.8–128.5)	14.6 ± 14.0	(1.3–42.0)	21	5
Puntioplites proctozysron	F8	89.1 ± 13.3	(79.1–108.6)	27.4 ± 13.6	(17.3–47.5)	4	1
Cyclocheilichthys armatus	F9	153.4	(150.8–156.0)	82.1	(65.5–98.6)	2	1
Parambassis wolffii	F10	102.3	(99.1–105.5)	39.0	(34.0–44.0)	2	1
Hemibagrus filamentus	F11	185.9		109.7		1	–
Cynoglossus sp. 1	F12	47.8 ± 9.8	(36.6–54.1)	1.2 ± 0.5	(0.7–1.6)	3	–
Cynoglossus sp. 2	F13	56.4 ± 14.1	(45.6–72.3)	1.7 ± 1.3	(0.7–3.2)	3	1
Pangasius micronema	F14	83.5		9.1		1	–
Osteochilus microcephalus	F15	92.5		19.1		1	–

[a] Number of samples for stable isotope analysis

[b] Number of samples for trace element analysis

concentrations of toxic elements such as Ag, Cd, Hg, Tl, and Pb were relatively low (<1.0 μg/l).

Phytoplankton, POM, five species of crustaceans, and nine species of fish were used for trace element analysis (Tables 1 and 3). The concentrations of several elements such as V, Mn, Co, As, Mo, Sn, Cs, Tl, Pb, and Bi were relatively high in POM. The concentrations of Mo, Sn, and Sb in phytoplankton, Cu, Sr, Ag, Cd, and Ba in crustaceans, and Cr, Rb, and Hg in fish were the highest among the organisms analyzed. Relatively high concentrations of Hg were observed in *Pisodonophis boro* (1.1 and 0.87 μg/g dry weight) compared to other fish species (<0.05–0.25 μg/g dry weight). Concentrations of Mn ($p < 0.01$), Cu ($p < 0.0001$), Zn ($p < 0.01$), As ($p < 0.0001$), Sr ($p < 0.0001$), Mo ($p < 0.01$), Ag ($p < 0.0001$), Cd ($p < 0.0001$), Sb ($p < 0.01$), Cs ($p < 0.05$), Ba ($p < 0.0001$), Tl ($p < 0.01$), and Pb ($p < 0.05$) were significantly higher in crustaceans than those in fish, whereas fish showed significantly higher concentrations of Cr ($p < 0.01$), Rb ($p < 0.001$), and Hg ($p < 0.05$) than crustaceans (Table 4, Fig. 3).

Biomagnification of Trace Elements

Relationships between the $\delta^{15}N$ and the log-transformed concentrations of trace elements were examined to investigate the trophic level-dependent accumulation of trace elements in the food web (Table 5). Concentrations of Se, Rb, and Hg increased with increasing $\delta^{15}N$ on both a wet- and a dry-weight basis (Fig. 4). In contrast, concentrations of Mn showed the opposite trend on a dry weight basis (Fig. 4). Trophic level-dependent accumulations of V, Cr, Co, Cu, Zn, As, Sr, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Tl, Pb, and Bi were not found in organisms collected from the Mekong River on either a wet- or a dry-weight basis.

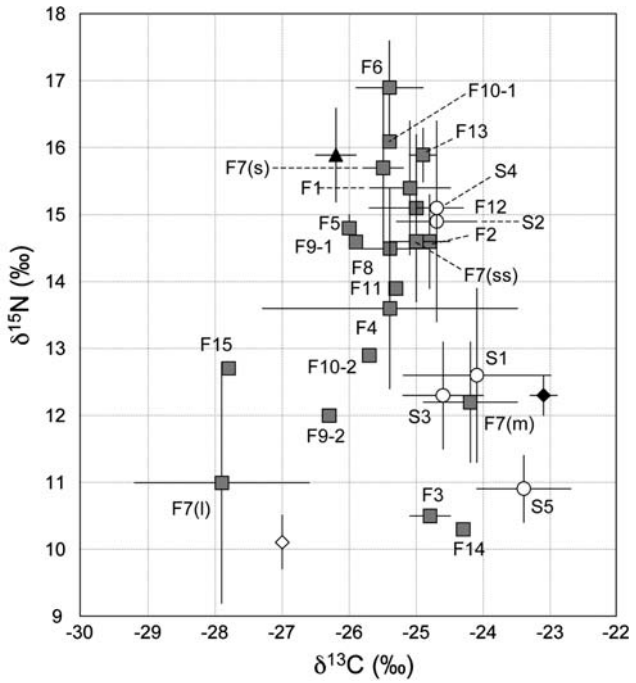

Fig. 2 Stable isotope diagram of the members of the aquatic food web in the Mekong Delta: δ^{15}N ‰ (mean ± SD) versus δ^{13}C ‰ (mean ± SD). Open diamond, phytoplankton; black diamond, POM; grey square, fish; open circle, shrimp; black triangle, snail. S1, *Macrobrachium rosenbergii*; S2, *M. equidens*; S3, *Macrobrachium* sp. 3; S4, *Macrobrachium* sp. 4; S5, *M. tenuis*; F1, *Clupeoides* sp.; F2, *Pisodonophis boro*; F3, *Rasbora aurotaenia*; F4 *Stenogobius mekongensis*; F5, *Eleotris melanosoma*; F6, *Polynemus paradiseus*; F7(ss), *Glossogobius aureus* (body length, 42.8–65.5 mm); F7(s), *G. aureus* (75.9–94.6 mm); F7(m), *G. aureus* (106.0–113.5 mm); F7(l), *G. aureus* (121.8–128.5 mm); F8 *Puntioplites proctozysron*; F9 *Cyclocheilichthys armatus*; F10, *Parambassis wolffii*; F11, *Hemibagrus filamentus*; F12, *Cynoglossus* sp. 1; F13, *Cynoglossus* sp. 2; F14 *Pangasius micronema*; F15, *Osteochilus microcephalus*

Table 2 Trace element concentrations (μg/l) in Mekong Delta water, South Vietnam

	Water 1	Water 2
V	1.0	1.1
Cr	0.60	0.59
Mn	3.58	3.55
Co	0.031	0.034
Cu	1.43	1.36
Zn	0.831	1.99
As	1.6	1.6
Se	0.60	0.52
Rb	2.57	2.56
Sr	119	121
Mo	0.458	0.460
Ag	<0.004	<0.004
Cd	0.005	0.008
Sn	0.033	0.059
Sb	0.30	0.34
Cs	<0.04	<0.04
Ba	24	26
Hg	<0.2	<0.2
Tl	0.008	0.007
Pb	<0.004	0.008
Bi	<0.004	<0.004

Discussion

Trace Element Concentrations in Biota

Concentrations of trace elements in the whole body of the fish and crustaceans sampled from the Mekong Delta were comparable with or lower than the values reported for fish and crustaceans around the world (Lin et al. 2001; Watanabe and Tanabe 2003; Pourang et al. 2004). However, concentrations of Cd in some Mekong Delta crustaceans were higher than the MAFF food guidelines (2000) (Cd, 0.2 μg/g wet wt; these data correspond to 0.8 μg/g dry weight for Cd, since moisture content is assumed to be 75% of wet weight). The whole body, not just the edible portion, was used to analyze the biomagnification of trace elements in this study and therefore a risk assessment of trace elements, especially Cd, was needed for humans and wildlife around the Mekong Delta using the edible portions of crustaceans. Concentrations of Hg and Pb in the study animals were lower than the MAFF guidelines (Hg, 0.3 μg/g wet weight; Pb, 2.0 μg/g wet weight for fish and 10 μg/g wet weight for shellfish, corresponding to 1.2 μg/g dry weight for Hg and 8.0 and 40 μg/g dry weight for Pb), but the highest level in *P. boro* (0.25 μg/g wet weight) was close to the MAFF guideline, so continuous monitoring of Hg may be needed for this species.

Comparison of Trace Element Concentrations in Crustaceans and Fish

Concentrations of trace elements differed between fish and crustaceans. The study revealed that concentrations of Mn, Cu, Zn, As, Sr, Mo, Ag, Cd, Sb, Cs, Ba, Tl, and Pb were higher in crustaceans, whereas fish showed higher concentrations of Cr, Rb, and Hg even when values were corrected for trophic level (using δ^{15}N values). It has been reported that V, Mn, Co, Cu, Se, Sr, Ag, Cd, Cs, and Ba concentrations are significantly higher in the hepatopancreas and muscle of invertebrates, including crustaceans and cephalopods, than those of deep-sea fish species from the western North Pacific, Japan (Watanabe et al. 2002). Petri and Zauke (1993) reported high Cd concentrations in 17 species of crustaceans in the Antarctic Ocean. Also, crustaceans from Japan apparently accumulate Cu, Sr, Cd,

Table 3 Trace element concentrations (mean ± SD μg g^{-1} dry wt.) in whole organisms of the Mekong Delta, South Vietnam. Values in parentheses indicate the range

	n	Moisture (%)	V	Cr	Mn	Co	Cu	Zn	As	Se	Rb	Sr
Phytoplankton	1	96.2	2.1	0.75	18.1	0.39	7.47	33.5	3.2	0.26	1.05	17.8
POM	1	74.8	15	18	436	4.6	14.8	41.6	12	0.56	27.1	36.2
Crustaceans												
M. rosenbergii	5	70.2	0.37 ± 0.19 (0.22–0.70)	4.8 ± 7.4 (1.2–18)	54.5 ± 14.3 (37–69.1)	0.21 ± 0.05 (0.13–0.26)	124 ± 33 (75.0–166)	82.7 ± 21.0 (53.7–109)	1.9 ± 0.7 (1.3–3.1)	0.73 ± 0.13 (0.58–0.92)	17.1 ± 4.1 (13.1–24)	433 ± 134 (345–662)
M. equidens	7	73.9	0.72 ± 0.43 (0.32–1.5)	0.91 ± 0.33 (0.50–1.4)	47.5 ± 20.5 (8.80–68.3)	0.28 ± 0.11 (0.12–0.46)	109 ± 20.0 (87.4–137)	145 ± 37 (113–223)	2.8 ± 1.0 (1.6–4.3)	0.97 ± 0.18 (0.69–1.2)	21.3 ± 2.3 (19.3–26.2)	375 ± 161 (85.0–595)
Macrobrachium sp. 3	2	71.4	0.24 (0.094–0.39)	1.3 (1.2–1.4)	96.9 (53.7–140)	0.15 (0.11–0.18)	161 (148–174)	83.9 (74.7–93.0)	1.6 (1.3–1.9)	0.80 (0.72–0.88)	18.9 (16.9–20.9)	443 (410–476)
Macrobrachium sp. 4	3	78.7	0.54 ± 0.37 (0.11–0.77)	1.1 ± 1.1 (0.19–2.3)	30.1 ± 7.7 (22.4–37.8)	0.20 ± 0.08 (0.12–0.27)	57.2 ± 10.5 (45.6–66.0)	87.5 ± 4.9 (82.3–92.0)	2.2 ± 0.2 (2.0–2.3)	1.4 ± 0.6 (0.84–2.0)	22.8 ± 3.0 (20.4–26.2)	332 ± 40 (302–377)
M. tenuis	1	75.2	0.11	0.27	17.3	0.18	54.5	49.1	2.2	0.93	17.9	207
Fishes												
Clupeoides sp.	1	81.9	0.38	0.47	25.6	0.10	3.48	117	1.0	0.89	27.4	83.7
P. boro	2	74.2	0.23 (0.22–0.23)	13 (8.2–17)	18.6 (17.7–19.4)	0.44 (0.39–0.49)	3.06 (2.79–3.32)	81.3 (71.1–91.5)	0.38 (0.32–0.43)	2.9 (2.4–3.3)	23.5 (19.7–27.3)	20.4 (17.5–23.2)
E. melanosoma	1	75.7	0.95	4.3	8.76	0.12	1.56	54.9	0.63	0.85	31.1	66.8
P. paradiseus	3	79.2	0.39 ± 0.11 (0.29–0.51)	13 ± 14 (0.44–29.0)	21.8 ± 1.1 (20.5–22.5)	0.17 ± 0.04 (0.13–0.21)	4.00 ± 0.60 (3.31–4.38)	59.9 ± 6.9 (52.1–65.4)	1.6 ± 0.3 (1.3–1.8)	1.4 ± 0.2 (1.1–1.5)	34.2 ± 3.7 (31.5–38.5)	128 ± 12 (116–139)
G. aureus	5	76.7	0.98 ± 0.33 (0.63–1.4)	11 ± 10 (1.6–23)	24.4 ± 5.6 (18.2–33.4)	0.20 ± 0.09 (0.10–0.35)	2.27 ± 0.33 (1.93–2.74)	75.0 ± 16.6 (60.4–101)	1.1 ± 0.3 (0.68–1.5)	0.91 ± 0.11 (0.78–1.0)	27.2 ± 5.8 (20.2–33.7)	95.8 ± 24.2 (78.4–138)
P. proctozysron	1	74.7	0.36	4.3	9.59	0.11	3.30	83.2	1.2	1.0	19.7	162
C. armatus	1	74.3	0.57	13	9.40	0.21	3.62	66.2	2.1	0.81	19.4	120
P. wolffii	1	76.9	0.20	4.6	47.9	0.079	2.19	72.2	0.51	0.65	35.3	334
Cynoglossus sp. 2	1	79.5	0.85	2.7	40.2	0.14	2.66	122	2.3	0.88	30.8	162

Table 3 continued

	Mo	Ag	Cd	Sn	Sb	Cs	Ba	Hg	Tl	Pb	Bi
Phytoplankton	0.246	0.020	0.308	0.228	0.07	0.05	33	<0.05	0.017	0.335	0.009
POM	0.069	0.096	0.240	0.280	<0.01	2.46	84	0.16	0.162	17.7	0.112
Crustaceans											
M. rosenbergii	0.138 ± 0.020 (0.119–0.167)	0.18 ± 0.05 (0.12–0.23)	0.720 ± 0.451 (0.252–1.26)	0.061 ± 0.050 (0.027–0.137)	0.02 ± 0.01 (0.01–0.03)	0.10 ± 0.04 (0.06–0.15)	130 ± 40 (78–180)	0.04 ± 0.04 (< 0.05–0.11)	0.025 ± 0.006 (0.017–0.032)	0.295 ± 0.203 (0.102–0.633)	0.007 ± 0.002 (0.003–0.009)
M. equidens	0.147 ± 0.018 (0.119–0.174)	0.19 ± 0.07 (0.10–0.30)	0.528 ± 0.119 (0.326–0.660)	0.054 ± 0.027 (0.026–0.088)	0.02 ± 0.00 (0.01–0.02)	0.15 ± 0.04 (0.11–0.22)	110 ± 50 (20–170)	0.08 ± 0.03 (< 0.05–0.11)	0.029 ± 0.006 (0.022–0.038)	0.396 ± 0.183 (0.206–0.732)	0.008 ± 0.004 (0.003–0.016)
Macrobrachium sp. 3	0.140 (0.103–0.177)	0.23 (0.17–0.29)	1.47 (0.827–2.11)	0.039 (0.038–0.039)	0.01 (< 0.01–0.01)	0.09 (0.07–0.10)	115 (110–120)	<0.05 (< 0.05–< 0.05)	0.021 (0.020–0.021)	0.098 (0.085–0.111)	0.007 (0.004–0.010)
Macrobrachium sp. 4	0.132 ± 0.057 (0.096–0.198)	0.16 ± 0.09 (0.091–0.26)	0.560 ± 0.316 (0.330–0.920)	0.146 ± 0.155 (0.049–0.324)	0.03 ± 0.03 (0.01–0.07)	0.13 ± 0.04 (0.09–0.17)	100 ± 30 (81–130)	0.06 ± 0 (< 0.05–0.08)	0.047 ± 0.016 (0.035–0.065)	0.412 ± 0.346 (0.112–0.791)	0.014 ± 0.013 (0.004–0.029)
M. tenuis	0.169	0.083	0.040	0.076	0.02	0.05	55	0.06	0.026	0.085	0.034
Fishes											
Clupeoides sp.	0.061	0.011	0.048	0.259	0.02	0.12	7.3	0.15	0.032	0.267	0.013
P. boro	0.143 (0.091–0.195)	0.007 (0.004–0.010)	0.019 (0.014–0.024)	0.039 (0.036–0.041)	<0.01 (< 0.01–< 0.01)	0.07 (0.07–0.07)	2.7 (2.5–2.9)	0.99 (0.87–1.1)	0.010 (0.010–0.010)	0.121 (0.108–0.134)	0.009 (0.008–0.009)
E. melanosoma	0.115	0.007	0.042	0.049	<0.01	0.12	13	0.13	0.017	0.180	0.009
P. paradiseus	0.081 ± 0.026 (0.061–0.11)	0.009 ± 0.003 (0.007–0.012)	0.035 ± 0.006 (0.029–0.040)	0.081 ± 0.013 (0.066–0.091)	0.01 ± 0.01 (0.01–0.02)	0.12 ± 0.01 (0.12–0.13)	25 ± 4 (21–29)	0.12 ± 0.02 (0.11–0.14)	0.042 ± 0.004 (0.039–0.047)	0.358 ± 0.093 (0.256–0.438)	0.010 ± 0.001 (0.009–0.010)
G. aureus	0.077 ± 0.066 (0.038–0.194)	0.004 ± 0.001 (0.003–0.006)	0.034 ± 0.009 (0.027–0.050)	0.086 ± 0.059 (0.027–0.181)	0.01 ± 0.00 (<0.01–0.01)	0.09 ± 0.02 (0.07–0.12)	16 ± 3 (13–21)	0.15 ± 0.06 (0.08–0.21)	0.014 ± 0.005 (0.007–0.020)	0.225 ± 0.067 (0.133–0.295)	0.013 ± 0.009 (0.007–0.029)
P. proctozysron	0.101	0.003	0.061	0.053	<0.01	0.07	12	0.11	0.012	0.268	0.009
C. armatus	0.105	0.008	0.034	0.063	<0.01	0.07	16	0.17	0.023	0.154	0.006
P. wolffii	0.060	<0.001	0.007	0.081	<0.01	0.19	56	0.22	0.015	0.078	0.013
Cynoglossus sp. 2	0.142	0.004	0.043	0.043	0.01	0.09	24	0.15	0.050	0.336	0.006

Table 4 Statistics for the regression between the trace element concentrations and $\delta^{15}N$ values of the crustaceans and fish of the Mekong Delta, South Vietnam

Elements	n	Wet weight basis				Dry weight basis			
		Slope	Intercept	r	p-value	Slope	Intercept	r	p-value
Crustaceans									
Log_{10} V	18	0.070	−1.958	0.370	0.130	**0.087**	−1.617	0.477	0.046
Log_{10} Cr	18	−0.080	0.566	0.334	0.176	−0.062	0.894	0.281	0.260
Log_{10} Mn	18	−0.061	1.895	0.363	0.139	−0.044	2.247	0.307	0.215
Log_{10} Co	18	0	−1.258	0.002	0.993	0.016	−0.908	0.178	0.480
Log_{10} Cu	18	−0.043	2.011	0.382	0.118	−0.026	2.362	0.285	0.253
Log_{10} Zn	18	0.022	1.110	0.249	0.318	0.039	1.462	0.444	0.065
Log_{10} As	18	0.017	−0.486	0.235	0.349	0.034	−0.141	0.423	0.080
Log_{10} Se	18	0.014	−0.815	0.236	0.345	0.030	−0.455	0.440	0.068
Log_{10} Rb	18	0.010	0.579	0.295	0.235	**0.026**	0.931	0.617	0.006
Log_{10} Sr	18	−0.022	2.275	0.174	0.489	−0.005	2.626	0.053	0.836
Log_{10} Mo	18	−0.023	−1.113	0.376	0.125	−0.007	−0.761	0.140	0.580
Log_{10} Ag	18	−0.006	−1.270	0.059	0.817	0.011	−0.929	0.116	0.647
Log_{10} Cd	18	0.028	−1.259	0.137	0.589	0.045	−0.911	0.227	0.366
Log_{10} Sn	18	0.041	−2.412	0.274	0.271	0.057	−2.061	0.365	0.137
Log_{10} Sb	18	0.010	−2.522	0.069	0.787	0.028	−2.201	0.206	0.413
Log_{10} Cs	18	**0.054**	−2.283	0.568	0.014	**0.069**	−1.916	0.735	<0.001
Log_{10} Ba	18	−0.014	1.617	0.101	0.690	0.002	1.975	0.019	0.941
Log_{10} Hg	18 (4)	0.064	−2.775	0.451	0.061	**0.080**	−2.420	0.526	0.025
Log_{10} Tl	18	0.017	−2.371	0.273	0.273	0.034	−2.016	0.450	0.061
Log_{10} Pb	18	0.065	−2.078	0.373	0.127	**0.082**	−1.728	0.482	0.043
Log_{10} Bi	18	−0.043	−2.090	0.263	0.291	−0.027	−1.727	0.171	0.498
Fishes									
Log_{10} V	16	−0.015	−0.706	0.077	0.776	−0.005	−0.218	0.024	0.928
Log_{10} Cr	16	−0.056	0.923	0.136	0.615	−0.047	1.425	0.120	0.659
Log_{10} Mn	16	−0.020	0.975	0.151	0.578	−0.011	1.481	0.076	0.870
Log_{10} Co	16	−0.014	1.195	0.081	0.766	−0.006	−0.675	0.036	0.894
Log_{10} Cu	16	0.027	−0.600	0.321	0.225	0.036	−0.092	0.400	0.125
Log_{10} Zn	16	−0.025	1.602	0.337	0.202	−0.016	2.111	0.206	0.443
Log_{10} As	16	0.056	−1.468	0.328	0.215	0.064	−0.955	0.365	0.164
Log_{10} Se	16	0.029	−1.035	0.205	0.447	0.039	−0.541	0.294	0.269
Log_{10} Rb	16	0.025	0.428	0.411	0.114	0.034	0.934	0.481	0.059
Log_{10} Sr	16	−0.004	1.390	0.019	0.944	0.005	1.898	0.023	0.933
Log_{10} Mo	16	−0.008	−1.595	0.051	0.852	0	−1.086	0.002	0.993
Log_{10} Ag	16 (1)	0.093	−4.345	0.406	0.119	0.102	−3.838	0.439	0.089
Log_{10} Cd	16	0.055	−2.981	0.351	0.182	0.063	−2.461	0.399	0.126
Log_{10} Sn	16	−0.001	−1.797	0.005	0.985	0.008	−1.293	0.048	0.861
Log_{10} Sb	16 (6)	0.048	−3.515	0.374	0.154	0.006	−3.045	0.388	0.137
Log_{10} Cs	16	0.012	−1.838	0.149	0.583	0.022	−1.347	0.241	0.368
Log_{10} Ba	16	0.007	0.410	0.028	0.917	0.015	0.931	0.061	0.821
Log_{10} Hg	16 (5)	0.006	−1.482	0.025	0.926	0.014	−0.967	0.064	0.813
Log_{10} Tl	16	**0.108**	−3.992	0.660	0.005	**0.118**	−3.493	0.636	0.008
Log_{10} Pb	16	**0.073**	−2.418	0.565	0.023	**0.082**	−1.910	0.567	0.022
Log_{10} Bi	16	**0.057**	−1.801	0.514	0.042	−0.048	−1.297	0.434	0.093

Numbers of samples under the detection limit concentration are given in parentheses

Bold numbers for slope indicate a significant difference ($p < 0.05$)

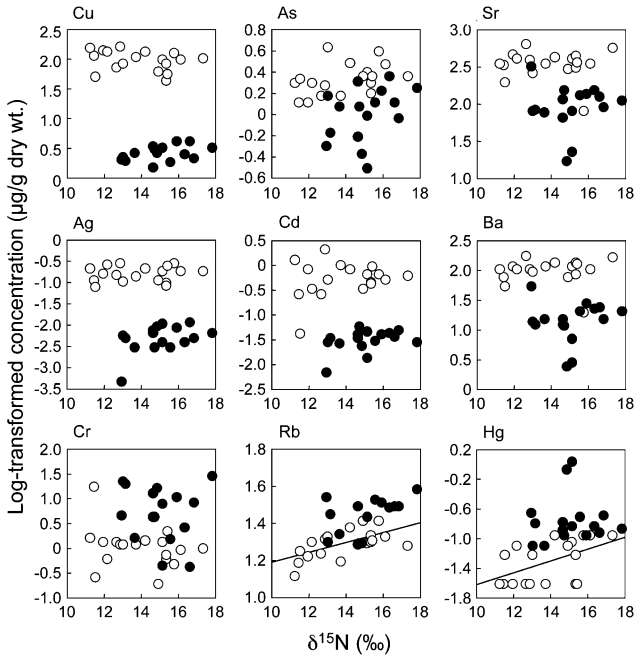

Fig. 3 Comparison of the relationship between δ^{15}N and the log-transformed trace element concentrations (µg/g dry weight) in crustaceans and fish in the Mekong Delta. Open circle, crustaceans; closed circle, fish

and Zn in relatively high concentrations in their edible parts (Ikebe et al. 1991). Such differences in trace element concentrations between fish and crustaceans might be attributable to differences in the metal accumulation and detoxification abilities such as those conferred by possessing metal-binding proteins, e.g., metallothioneins (MT), that can bind and sequester toxic and excess heavy metals. Metallothioneins are found in almost all major invertebrate phyla as well as in all vertebrates (Binz and Kägi 1999; Amiard et al. 2006). Also, crustaceans have a high requirement for Cu as it is part of their respiratory pigment, hemocyanin (Rainer and Brouwer 1993), and Cu-specific MT, intricately involved in Cu homeostasis associated with both the synthesis and degradation hemocyanin, was found in the blue crab (Brouwer et al. 2002). Furthermore, a great number of invertebrate species are known to contain metal-rich granules (Cu, Zn, Ag, Cd and Hg) in which metals are sequestered in a detoxified form (Brown 1982; Rainbow 1996; Ahearn et al. 2004). These granules are generally found in the epithelial cells of such organs as the crustacean hepatopancreas or kidney (Ahearn et al. 2004). The higher concentrations of Sr and Ba observed in crustaceans may result because the behavior of these elements is similar to that of Ca in animals; it is conceivable

Table 5 Statistics for the regression between the trace element concentrations and δ^{15}N values of the biota of the Mekong Delta, South Vietnam

Elements	n	Wet weight basis				Dry weight basis			
		Slope	Intercept	r	$p-$value	Slope	Intercept	r	$p-$value
Log_{10} V	36	0.015	−1.131	0.069	0.689	0.004	−0.345	0.018	0.919
Log_{10} Cr	36	0.027	−0.643	0.077	0.654	0.015	0.156	0.046	0.790
Log_{10} Mn	36	−0.048	1.563	0.221	0.196	**−0.060**	2.371	0.330	0.049
Log_{10} Co	36	−0.020	−1.012	0.114	0.506	−0.032	−0.218	0.197	0.249
Log_{10} Cu	36	−0.102	2.070	0.227	0.182	−0.114	2.873	0.272	0.109
Log_{10} Zn	36	0.031	0.781	0.252	0.138	0.023	1.584	0.258	0.128
Log_{10} As	36	−0.007	−0.324	0.038	0.824	−0.020	0.498	0.127	0.466
Log_{10} Se	36	**0.066**	−1.599	0.443	0.007	**0.052**	−0.770	0.535	<0.001
Log_{10} Rb	36	**0.088**	−0.565	0.451	0.006	**0.077**	0.233	0.575	<0.001
Log_{10} Sr	36	0.010	1.454	0.037	0.832	−0.002	2.262	0.010	0.954
Log_{10} Mo	36	−0.018	−1.335	0.140	0.416	−0.030	−0.533	0.276	0.103
Log_{10} Ag	36 (1)	−0.081	−0.963	0.180	0.293	−0.092	−0.178	0.216	0.205
Log_{10} Cd	36	−0.064	−0.566	0.170	0.320	−0.076	0.237	0.213	0.213
Log_{10} Sn	36	0.019	−2.091	0.133	0.440	0.007	−1.287	0.044	0.797
Log_{10} Sb	36 (7)	−0.013	−2.403	0.081	0.639	−0.021	−1.652	0.125	0.468
Log_{10} Cs	36	0.035	−2.075	0.191	0.264	0.023	−1.281	0.154	0.369
Log_{10} Ba	36	−0.054	1.750	0.183	0.285	−0.066	2.552	0.247	0.147
Log_{10} Hg	36 (10)	**0.114**	−3.303	0.480	0.003	**0.101**	−2.496	0.464	0.004
Log_{10} Tl	36	0.034	−2.730	0.217	0.204	0.023	−1.941	0.168	0.326
Log_{10} Pb	36	0.030	−1.639	0.132	0.442	0.018	−0.833	0.083	0.631
Log_{10} Bi	36	−0.022	−2.350	0.124	0.471	−0.037	−1.514	0.230	0.177

Numbers of samples under the detection limit concentration are given in parentheses

Bold numbers for slope indicate a significant difference ($p < 0.05$)

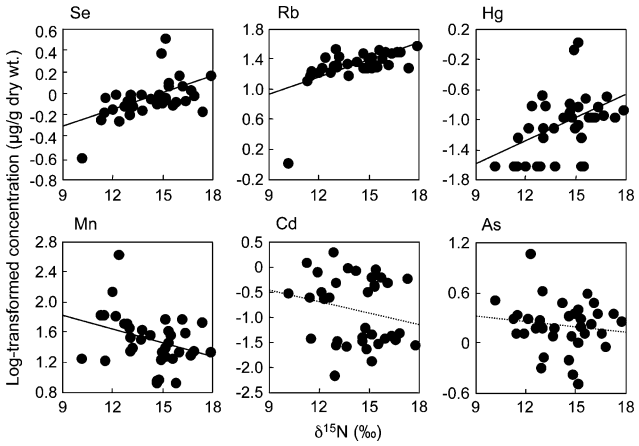

Fig. 4 Relationships between δ^{15}N and log-transformed trace element concentrations (μg/g dry weight) in biota from the Mekong Delta

that Sr and Ba were used along with Ca for the formation of the exoskeleton.

Biomagnification of Trace Elements

It is generally accepted that Hg concentrations in biota depend on trophic levels (Suedel et al. 1994; Cabana and Rasmussen 1994; Atwell et al. 1998). A significant positive linear relationship between δ^{15}N values and Hg concentration was observed in the organisms of the Mekong Delta food web, indicating that an overall biomagnification of Hg had occurred. The slope of the regression function of the log-transformed Hg concentration on δ^{15}N (0.114, wet weight basis) is smaller than that found for Arctic marine food webs (0.197–0.32) (Jarman et al. 1996; Atwell et al. 1998; Campbell et al. 2005a), for biota of Papua New Guinea (0.21) (Yoshinaga et al. 1992), for freshwater fish from several lakes in North America (0.2–0.3) (Kidd et al. 1995b) and for freshwater fish and bivalves from Lake Chad in Africa (0.21) (Kidd et al. 2004). The difference between this study and those cited might reflect the different compositions of the food webs and/or differences in growth rate. Some of these studies have analyzed marine mammals and seabirds (Yoshinaga et al. 1992; Jarman et al. 1996; Atwell et al. 1998; Campbell et al. 2005a), organisms known to specifically accumulate large amounts of Hg in their tissues (Ikemoto et al. 2004; Arai et al. 2004). Some studies even report high concentrations in the muscle tissues (Itano et al. 1984; Kim et al. 1996). In general, organisms in tropical areas show faster growth, which might lead to less biomaginfication of Hg even at a higher trophic level.

Selenium and Rb also underwent biomagnification in the study ecosystem. Stewart et al. (2004) found significant positive correlations between Se concentrations and δ^{15}N in San Francisco Bay food webs and, recently, the biomagnification of Rb was noted in aquatic ecosystems (Campbell et al. 2005a, 2005b). The slope of the regression line of the log-transformed element concentrations on δ^{15}N was 0.066 for Se and 0.088 for Rb in the present study, suggesting that biomagnification power decreases sequentially as Hg > Rb > Se.

Concentrations of Mn decreased with increases in trophic level. A trophic level-dependent accumulation of Mn was not observed in an Arctic marine food web (Campbell et al. 2005a) nor in the biota of Papua New Guinea (Yoshinaga et al. 1992). Since Mn is an essential element, required as a cofactor of some enzymes (Barceloux 1999), most biota, especially animals situated in the middle to higher part of the food chain, might have the ability to regulate the concentration of Mn. However, future study is necessary to determine why the concentration of Mn in higher trophic animals decreases.

Other elements such as V, Cr, Mn, Co, Cu, Zn, As, Sr, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Tl, Pb, and Bi were not biomagnified or biodiluted through the food chain in the Mekong Delta. Campbell et al. (2005a) reported biomagnification of Zn and biodilution of Cd and Pb in an Arctic marine food web, and the same trends for Zn and Cd were also seen in the biota of Papua New Guinea (Yoshinaga et al. 1992). In contrast, Quinn et al. (2003) reported trophic level-dependent accumulation of Zn in a freshwater stream in North America. Arsenic, one of the most significant toxic elements in this region, with biomagnification potential (Suedel et al. 1994), was not biomagnified in the Mekong Delta organisms.

The biomagnification of trace elements in the biota of the Mekong Delta watershed revealed in this study suggests that more research of the influences of the elements on the ecosystems and human life is required for various ecosystems of the world.

Acknowledgments We are grateful to Dr T. Komai for identifying the crustaceans. The study was supported by a grant from Research Revolution 2002 (RR2002) of the Project for Sustainable Coexistence of Human, Nature and Earth (FY2002) from the Ministry of Education, Culture, Sports, Science and Technology, Japan and by a Grant-in-Aid for Scientific Research from the Japan Society for Promotion of Science (no. 16310042).

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